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BEAM-BASED ALIGNMENT TECHNIQUES FOR THE FCC-ee

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Abstract

The Future electron-positron Circular Collider (FCC-ee) is a proposed lepton collider for high-energy particle physics succeeding the Large Hadron Collider (LHC). Its ambitious design goals demand excellent orbit and optics control and, therefore, set strict limits on alignment tolerances. One approach to relax the mechanical alignment tolerances is Beam-Based Alignment (BBA), where the offset between magnet and position measurement is determined and can later be used to steer the beam towards the magnetic centre using corrector magnets. One of the key challenges of the FCC-ee is developing an accurate and fast BBA strategy for quadrupoles and sextupoles. A parallel BBA technique is evaluated and compared in simulations for the baseline and an alternative lattice for FCC-ee using Xsuite and is presented in this paper.

INTRODUCTION

The Future electron-positron Circular Collider (FCC-ee) is a possible future collider with a circumference of about 91 km within the framework of the FCC design study [1–3]. The FCC-ee is being designed to operate with beam energies from 45.6 GeV to 182.5 GeV and aims for a luminosity of up to $1.44 \cdot 10^{36}\,\mathrm{cm^{-2}\,s^{-1}}$ at 45.6 GeV [4]. This sets strict boundaries on the accelerator optics and, thus, also on alignment tolerances of all lattice elements. In particular, these constraints apply to the maximum magnet misalignments and the required accuracy for the transversal offset of quadrupoles and sextupoles in the range from 10 µm to 20 µm of the Beam-Based Alignment (BBA) [4, 5]. Two different lattices are proposed for FCC-ee, namely the so-called the Global Hybrid Correction (GHC) [6] and the Local Chromaticity Correction (LCC) [7] lattice. The GHC lattice is the current baseline in the Feasibility Study Report; the LCC is an alternative lattice, which is, in general, less sensitive to magnet misalignments in the arc regions [4, 7].

Beams passing off-centre through multipole magnets experience additional field components with lower orders than the misaligned magnets, causing additional deflections and focusing, resulting in orbit and optics deviations. BBA is used to reduce the offset between the magnetic centre and the particle beam by steering it towards the magnetic centre using orbit correctors [8–10]. Transversely misaligned quadrupoles introduce additional dipole fields due to feed-down, which lead to closed orbit pertubations, which in turn via feed-down from strong sextupoles change even the tunes. A fast and accurate determination of the beam offset relative to the magnetic centre is the aim of the BBA studied here.

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Traditionally, BBA is performed on individual magnets [11]. An excitation of correctors allows a fast orbit change to reduce time required for BBA, in addition to a stepwise modulation of the quadrupole strength, as demonstrated at various synchrotron light sources such as ALBA [12] and Diamond [13]. Since the time required increases linearly with the number of quadrupoles, individual BBA is a very time-consuming procedure for larger machines like the FCC-ee. For example, LEP has used an excitation of multiple magnets with different frequencies to estimate offsets simultaneously [14]. In the past years, parallel BBA techniques are investigated for various machines, including EBS at ESRF [15] and SPEAR3 at SLAC [16]. Parallel BBA has also been simulated for the FCC-ee [17]. In this paper, an alternative approach for parallel BBA is considered, and simulation results for the arc sections of the two different FCC-ee lattices are presented.

BBA TECHNIQUE

The magnetic field of a quadrupole experienced by a beam passing with a horizontal offset $x \mapsto x' = x + x_0$ is:

$$\vec{B}' = \begin{pmatrix} ky \\ kx' \\ 0 \end{pmatrix} = \begin{pmatrix} ky \\ kx + kx_0 \\ 0 \end{pmatrix} = \underbrace{\begin{pmatrix} ky \\ kx \\ 0 \end{pmatrix}}_{\text{Quadrupole}} + \underbrace{\begin{pmatrix} 0 \\ kx_0 \\ 0 \end{pmatrix}}_{\substack{\text{Dipole with} \\ B_y = kx_0}} . \quad (1)$$

In addition to the focusing or defocusing quadrupole field, the additional position-dependent dipole field deflects the beam. One option proposes the vertical orbit correctors in the quadrupoles in the form of additional trim windings. The challenge here is the cross-talk between the two apertures, causing a horizontal movement of the magnetic centre affecting both beams and the skew-sextupole components [18]. In this configuration, the quadrupole and dipole fields are superimposed in the magnet. This arrangement allows the compensation of the kick experienced by the non-centre-passing particle beam to be corrected by the orbit corrector with the aim of keeping the orbit constant.

The approach presented here for the BBA uses the possibility of determining the offset of the beam relative to the magnetic centre by the dependence of the corrector field strength on the quadrupole strength. During the BBA, in the first step the quadrupole strength is varied. Afterwards the strength of the orbit correctors in the modulated quadrupoles is adjusted so that the orbit does not change. Changes in the orbit corrector strengths are thus exclusively due to the changed deflection in the quadrupoles, which magnet strengths are varied. The proportionality factor between the quadrupole strength changes and the corrector strength changes is the offset. The approach allows both individual and parallel

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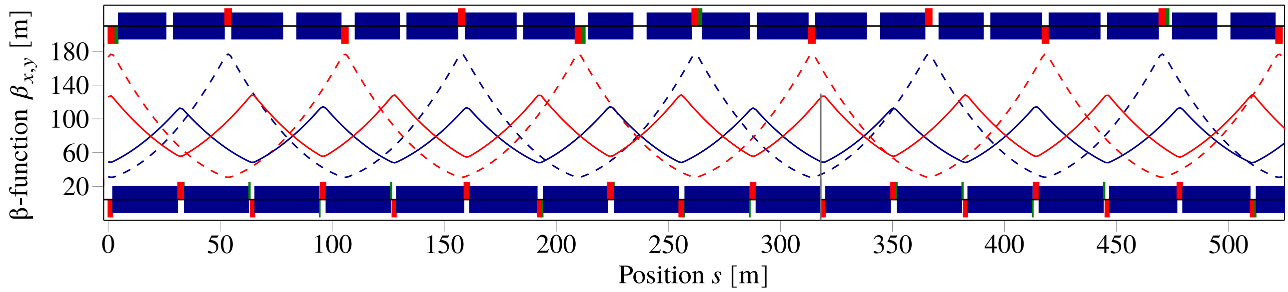

Figure 1: Lattice for one supercell of the GHC lattice (upper sketch) and more than one of the LCC lattice (lower sketch, the region between 0 m and 318 m is one cell) as well as the horizontal (blue) and vertical (red) β-functions for GHC (dashed) and LCC (solid) lattice.

BBA. The BBA requires a sufficient number of BPMs between the modulated quadrupoles for a reliable correction of the orbit changes. The constant orbit avoids influences from other elements such as sextupoles. As an alternative to orbit correctors integrated in the quadrupole, a lattice with separate horizontal and vertical orbit corrections just behind the quadrupole is considered. The quadrupolar and dipolar fields of the quadrupole and orbit corrector do not overlap, so a reduction in accuracy is expected.

SIMULATION SETTINGS

The BBA for the two different lattices proposed for FCC-ee, GHC and LCC, (both version V24.3) [19] are compared. A schematic of the arc lattice and the β-functions are shown for both lattices in Fig. 1. The optics used for the simulations are designed for a beam energy of 45.6 GeV, and have a larger β^* in the interaction points than the optics optimised for high luminosity and are intended to be used for commissioning of the collider. For both lattices, the minimum vertical β-function β^*_y at the interaction point is 7 mm, and the horizontal β-function β^*_x is 33 cm for the GHC and 30 cm for the LCC optics.

For the Xsuite [20] simulations, the quadrupoles are misaligned with a random, normally distributed offset with a standard deviation of 100 µm using 51 different seeds; sextupoles and BPMs are not misaligned and synchrotron radiation is deactivated. For the GHC Lattice, the BPM and orbit correctors are inserted 10 cm behind the quadrupoles and for the LCC at the end of the quadrupoles. The closed orbit is determined for each of the differently misaligned lattices using beam threading and orbit correction. For all LCC and GHC simulations with deactivated sextupoles, the closed orbit was determined for all seeds using the method. With sextupoles switched on, no closed orbit was found for 11 seeds using the GHC lattice. It was always possible to perform the BBA if a closed orbit was initially found. After the initial orbit correction, the horizontal (vertical) rms orbit is 1.28(3) µm (6(5) µm) for LCC and 1.93(4) µm (2.2(9) µm) for GHC. The larger vertical rms orbit for the LCC lattice is attributed to a non-optimal orbit response matrix used for the orbit correction. For each of the differently misaligned lattices, the BBA described above is performed, using a relative change of the quadrupole strength in the range from 0.4 % to 1.1 % and a BPM resolution of 1 µm. The BBA approach is used to determine the offset of the beam relative to the magnetic centre. The difference between the actual and the value found applying the BBA is used for all further analyses. In a further step, the rms value is calculated for certain magnet groups or different seeds. Two different variants for the arcs alternate in the GHC lattice and each consist of quadrupoles from two families. The difference lies in the length of the arcs, which differs by 2.5 FODO cells, and the naming, in one version the magnet families are named QD1 and QF2, in the other QD3 and QF4. The LCC lattice has eight identical arcs based on 3 focusing and 3 defocusing quadrupole families. The strengths and lengths of the arc quadrupoles are given in Table 1.

Table 1: Magnet Strength and Lengths of the Different Arc Quadrupole Families for the GHC and LCC Optics at Z

Quadrupole family	Strength in T m^{-1} GHC	Strength in T m^{-1} LCC	Length in m GHC	Length in m LCC
QD1	−1.451	−2.020	2.90	2 × 0.96
QF2	1.451	1.690	2.90	2.39
QD3	−1.451	−2.071	2.90	1.86
QF4	1.451	1.709	2.90	2.40
QD5		−2.107		1.83
QF6		1.696		2.37

RESULTS FOR QUADRUPOLE BBA

In the horizontal plane, the BBA for two arc sections for the quadrupole families QD3 and QF4 is simulated for both lattices, but all arc quadrupoles are misaligned. For GHC, there are 87 and 88 quadrupoles, respectively, and for LCC, 54 per arc and family. The BBA determines the offsets in parallel for every one to every sixth magnet, i.e., for nine to 88 magnets equally distributed over the arc in parallel. In the simulation, the change in quadrupole strength is varied in the range from ±0.4 % to ±1.1 % and every third magnet of the families QD3 and QF4 is used for the parallel BBA. The results are shown in Fig. 2. No dependence on the amplitude is found for the horizontal LCC BBA, while a stronger quadrupole modulation is favourable for the ver-

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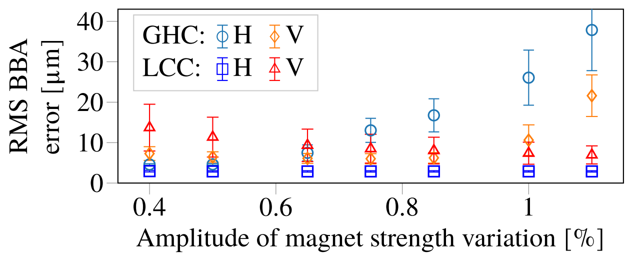

Figure 2: Dependence of horizontal (h) and vertical (v) BBA accuracy on amplitude of quadrupole strength variation for LCC and GHC.

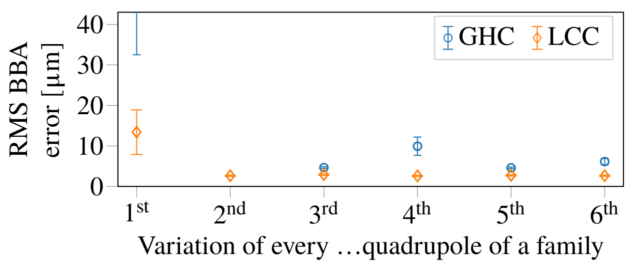

Figure 3: Dependence of horizontal BBA accuracy on number and distance between modulated quadrupoles.

tical quadrupole BBA. In contrast, for the GHC lattice, a strong increase in error and uncertainty for the horizontal BBA is observed for larger quadrupole strength modulations. Smaller amplitudes of the relative magnetic strength change in the range of ±0.4 % to ±0.5 % should, therefore, be used for applying BBA to the GHC lattice. In the vertical plane, an amplitude in the range from ±0.4 % to ±0.85 % should be chosen. When selecting the modulation amplitude of the quadrupoles, a trade-off must be made between a sufficiently large change, in which BPM noise and the accuracy of the corrector strengths play a lesser role, and a sufficiently small change so that the accelerator optics are not changed too much. The range for favourable values differs for the two lattices, while a value in the range from ±0.4 % to ±0.65 % appears to be a favourable choice for GHC, the amplitude of the quadrupole change should be at least 1 % for LCC.

Based on the previous consideration of the dependence of the accuracy of the BBA on the amplitude of the quadrupole strength variation, these results are taken into account for the following simulation. The relative change in quadrupole strength is set to ±1 % for the LCC and to 0.5 % for the GHC lattice. In the first step, the rms of the difference between the beam to quadrupole offset from the reconstruction and the real offset is determined for all magnets. The mean value and the standard deviation of the rms values for the different seeds are then determined and shown in the graphs as a value or error bar. The results are shown in Fig. 3. We note that modulating all magnets simultaneously for BBA leads to large errors for the offset determination. Significantly smaller deviations are observed if the number of modulated magnets is reduced and the distances between them increased. If each quadrupole is varied, the rms deviation is 13 µm and 115 µm for LCC and GHC respectively and is reduced to around 3 µm if every second or fewer magnets are modulated in parallel for LCC and to less than 10 µm for every third or fewer magnets for GHC. In all cases, the deviations for GHC are larger than for LCC.

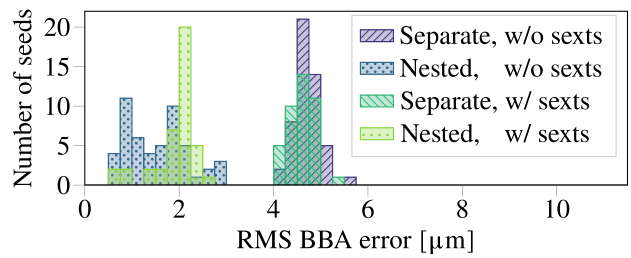

Figure 4: Dependence of vertical BBA accuracy on corrector location with activated and deactivated sextupoles.

Various options of orbit correctors are being investigated. Vertical orbit correctors could be nested with quadrupoles, sextupoles or installed as individual elements. Horizontal orbit correctors could be integrated with sextupoles, dipoles or could be integrated as individual elements. Figure 4 shows the results for the vertical BBA for two different positions of the orbit correctors, which are nested in the quadrupoles or located 10 cm behind the quadrupoles. Simulations are performed for the GHC lattice, modulating every ninth magnet of a family over 2 arcs, leading to 20 magnets in total. The relative quadrupole strength variation is ±0.8 %. Significantly larger errors of the reconstructed offset were observed for the first and last magnets of the selected group in the vertical BBA than for all magnets in between, which were therefore excluded for the calculation of the rms values. These deviations depend on the selection of the BPM and are probably due to orbit changes caused by the BBA in other arcs and the Interaction Regions (IR). Due to the approximately constant beam position during the BBA, powering sextupoles have negligible impact. When comparing nested and separated orbit correctors, the rms BBA error is slightly higher for separated orbit correctors, but well below 10 µm.

With the magnet selections used here, 9 to 54 quadrupoles are modulated in parallel for LCC and 14 to 88 for GHC. Compared to an identical individual BBA approach, the time required is reduced by a factor corresponding to the number of magnets modulated in parallel.

SUMMARY AND OUTLOOK

Based on the first simulation results with small misalignments, we conclude that the targeted accuracy in the range of 10 µm to 20 µm is achievable. Further studies should consider alternative positioning of the orbit correctors, realistic misalignment of quadrupoles, sextupoles, dipoles, girders and BPM, and testing different magnet selections, in particular different numbers of consecutive magnets. A further step is the application of the presented BBA approach to the currently not yet studied interaction regions and the development of a sextupole BBA for the arcs and IRs.

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